

## **New insights in high-resolution spectroscopy: a wide theoretical library of R=500 000 stellar spectra**

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### **Abstract.**

We present an extended theoretical library of over 800 synthetic stellar spectra, covering energy distribution in the optical range ( $\lambda = 3500 - 7000 \text{ \AA}$ ), at inverse resolution  $R=500\,000$ . The library, based on the ATLAS9 model atmospheres, has been computed with the SYNTHE code developed by R. L. Kurucz. The grid spans a large volume in the fundamental parameters space (i.e.  $T_{\text{eff}}$ ,  $\log g$ ,  $[M/H]$ ), and can be profitably applied to different research fields dealing both with the study of single stars and stellar aggregates, through population synthesis models. A complementary project, in progress, will extend the wavelength range to the ultraviolet, down to  $850 \text{ \AA}$ , at an inverse resolution of  $R=50\,000$ .

## **1. Introduction**

New-generation spectrographs, at the major ground-based telescopes, have begun to pour in the hard-disks of astronomers' computers an increasing mass of high-quality spectroscopic data. Inverse resolutions as high as  $\lambda/\Delta\lambda = 100\,000$  can now be easily attained, at least for the brightest ( $V \lesssim 15 \text{ mag}$ ) objects in the sky, and this is pushing the observation of local and extragalactic stellar systems to an ever unimagined resolution level. The outstanding performance of instruments like UVES and VIRMOS at the ESO Very Large Telescope, or HIRES and SARG at the Keck Observatory and Telescopio Nazionale Galileo, respectively, urges therefore theoretical tools of comparable accuracy level in order to consistently match and analyse such a huge amount of observational data.

In this framework, and to help filling the gap, we undertook a long-term project aimed at providing the community with a systematic theoretical library

of high-resolution stellar spectra (virtually the largest sample currently available in the literature) in the optical range ( $\lambda = 3500 \rightarrow 7000$  Å) and at an inverse resolution of  $R = 500\,000$ .

## 2. The optical grid of synthetic spectra

This first set of spectral energy distributions relied on the SYNTHE code of Kurucz (1993), using ATLAS 9 model atmospheres (Kurucz 1995) as input. Computations have been carried out at the Brera Observatory in Milan (Italy). The input models follow the classical approximations of steady-state, homogeneous, LTE, plane-parallel layers, with a microturbulence velocity of 2 km/s and a mixing-length value  $\ell/H_p = 1.25$ . They make use of an improved treatment of convective overshooting in the calculation of the transfer equations (Castelli, Gratton, & Kurucz 1997).

Over 46 million absorption lines are accounted for in the code, including all atomic elements at different ionization states and the most important diatomic molecules. All line data were extracted from the Kurucz' (1992) original database, with the major improvement of the TiO contribution, for which we adopted the new list of lines computed by Schwenke (1998).

The wavelength interval spans the whole optical range, from the Balmer break to  $H\alpha$ . All the passbands of the Lick/IDS spectrophotometric indices (Worthey et al. 1994) are included, as well as the high-resolution index set defined by Rose (1994). Spectra are sampled at variable wavelength step maintaining a constant resolution ( $\Delta\lambda/\lambda = 2 \times 10^{-6}$ ).

The library extends to effective temperatures as hot as  $T_{\text{eff}} = 50\,000$  K, and provides a suitable match to O  $\rightarrow$  K spectral types. M stars, cooler than  $T_{\text{eff}} < 4000$  K, are however still lacking in our dataset given the missing contribution of tri-atomic molecular opacity in the input model atmospheres (Kurucz 1992).

Gravity spans a wide range across the H-R diagram ( $5 \geq \log g \geq 0$ ), namely from dwarf (MK class V) to supergiant stars (MK class I), while metallicity accounts for stars at the two extreme edges of the Galaxy [Fe/H] distribution with  $-3.0 < [\text{M}/\text{H}] < +0.3$  as boundary limits. A total of 832 synthetic spectral energy distributions (SEDs) have been computed, as summarized in Fig. 1 and Table 1. An illustrative example of the model output, sampling the spectral emission around the atomic Mg *b* triplet, is shown in Fig. 2 and 3, with varying physical parameters.

A complementary project, which will extend our analysis to the ultraviolet interval, between 850–4750 Å with an inverse resolution  $R = 50\,000$ , is in progress at INAOE and will be completed soon (Rodríguez-Merino 2002). The extended dataset consists of over 1000 SEDs covering the effective temperature range between 3500 and 50 000 K at surface gravity  $\log g = 1.0 \rightarrow 5.0$  and chemical compositions  $[\text{M}/\text{H}] = +0.5, 0.0, -0.5$  and  $-1.5$  (Rodríguez-Merino et al. 2001). In Fig. 4 we display a subset of spectra computed for solar chemical composition,  $\log g = 5$  and different effective temperatures.

Table 1. The properties of the optical library of synthetic spectra.

Code:	SYNTH (Kurucz 1993)
Input models:	ATLAS9 (Kurucz 1995)
Wavelength range:	$3500 \leq \lambda \leq 7000 \text{ \AA}$
Resolution:	$R = \lambda/\Delta\lambda = 500\,000$
Wavelength step:	$0.007 \leq \Delta\lambda \leq 0.014 \text{ \AA}$
Wavelength points:	346 645
Total absorption lines:	$\sim 46$ millions
Molecules:	C <sub>2</sub> , CN, CO, CH, NH, OH, MgH, SiH, H <sub>2</sub> , SiO, TiO
Total number of spectra:	832
Effective temperature:	$4000 \leq T_{\text{eff}} \leq 50000 \text{ K}$
Surface gravity:	$0.0 \leq \log g \leq 5.0$
Metallicity:	$-3.0 \leq [\text{M}/\text{H}] \leq +0.3$

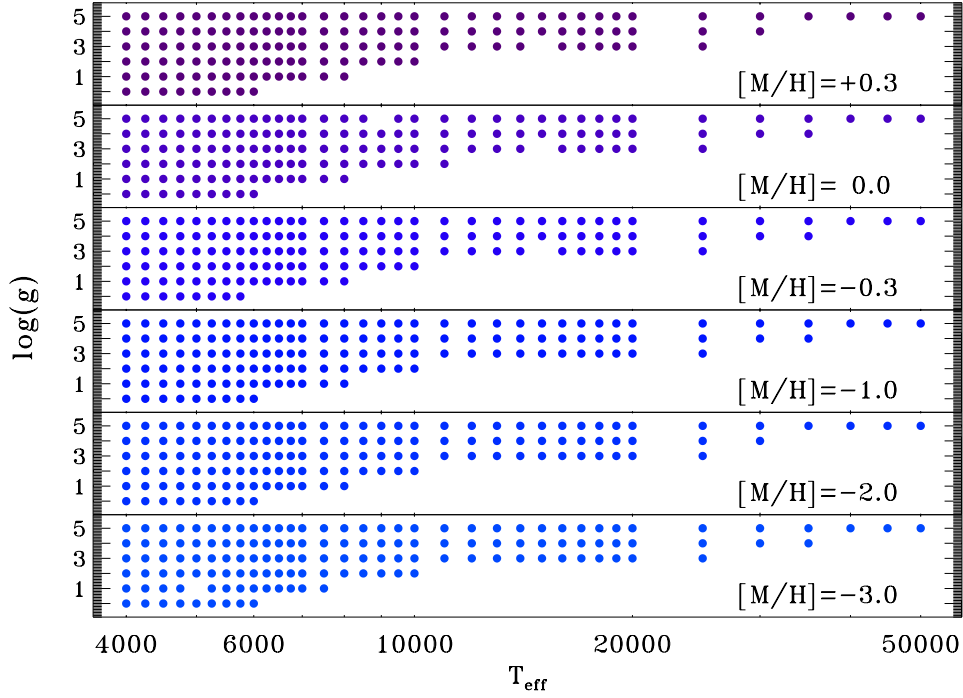


Figure 1. The optical library of synthetic high-resolution spectra. Each panel shows the model grid for fixed metallicity. The whole set consists of 832 SEDs.

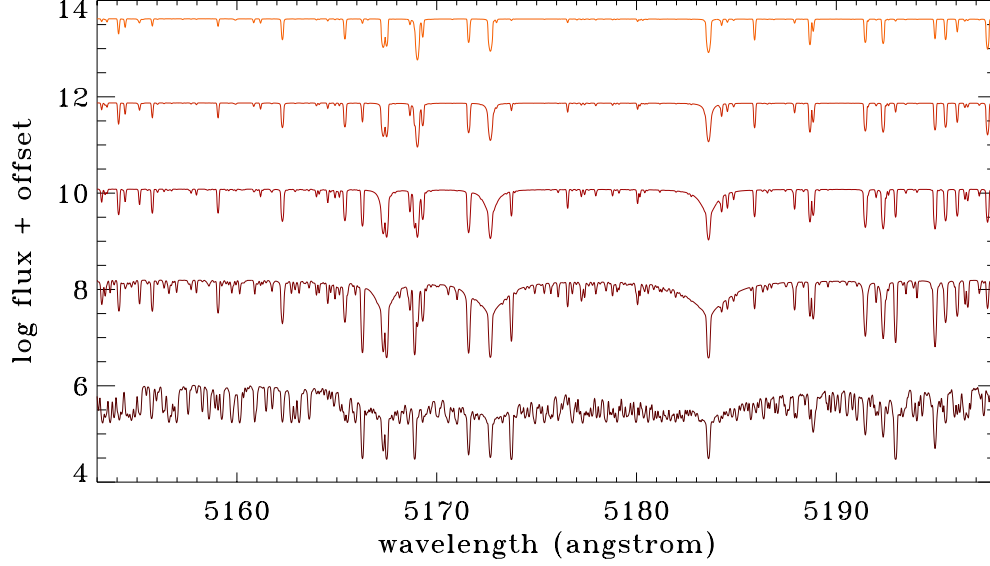


Figure 2. An illustrative sample of the synthetic spectra with solar metallicity, spanning the wavelength region around the atomic Mg *b* triplet. Increasing temperatures (bottom to top) from  $T_{\text{eff}} = 4000 \rightarrow 8000$  K at step of 1000 K are explored, with fixed gravity  $\log g = 4$ .

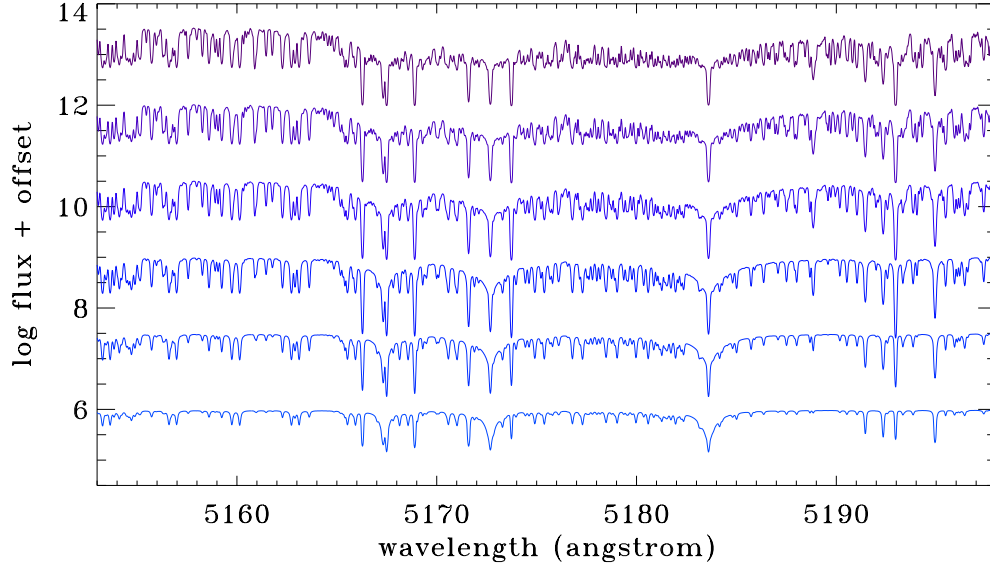


Figure 3. Same as in Fig. 2, but with varying metallicity, for  $T_{\text{eff}} = 4000$  K and  $\log g = 4$ . Metallicity values are  $[M/H] = -3.0, -2.0, -1.0, -0.3, 0.0, +0.3$  (bottom to top, respectively).

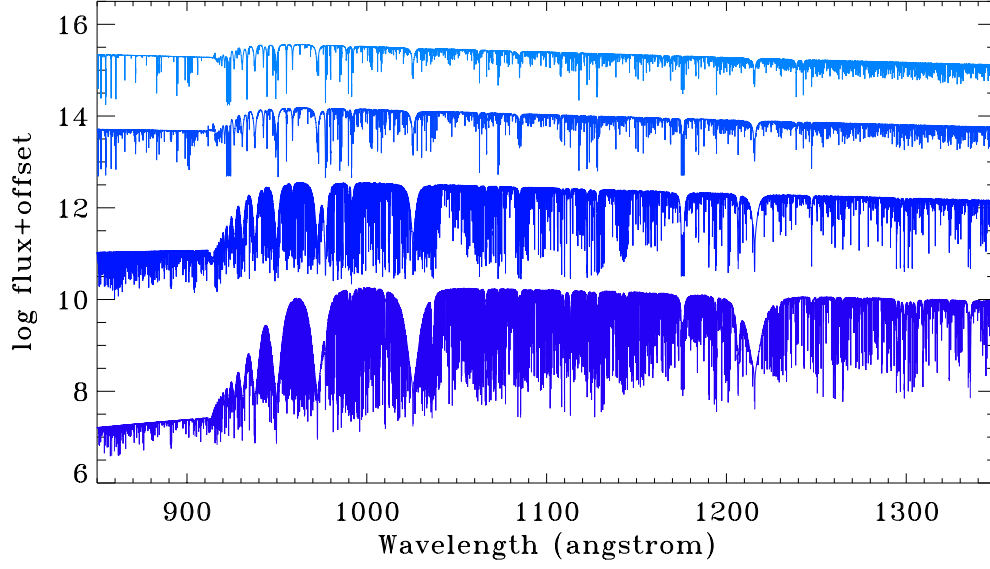


Figure 4. A sequence of high temperature spectra longward of the Lyman limit from the UV library. The models have fixed gravity ( $\log g = 5$ ) and solar chemical composition, while the effective temperature increases (bottom to top) from 20 000 to 50 000 K at step of 10 000 K.

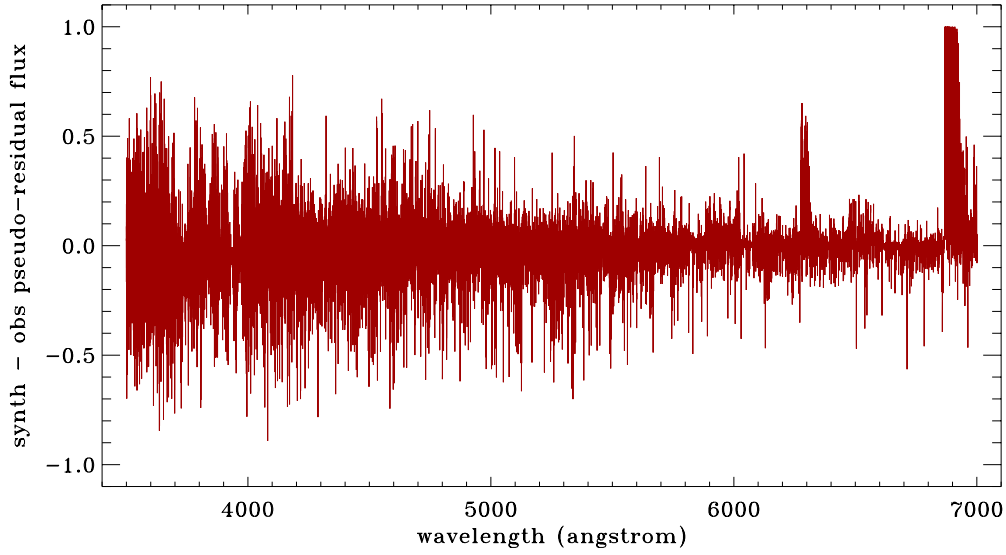


Figure 5. Difference in the pseudo-residual flux between the synthetic and the observed spectrum of the Sun (Kurucz et al. 1984) in the spectral region 3500–7000 Å. The features about 6300 and 6900 Å are due to telluric absorption bands in the observed spectrum.

### 3. The solar spectrum validation

A comparison with the solar spectrum represents a first mandatory test in order to assess the degree of reliability of our theoretical library. We present in Fig. 5 the match of the Solar Flux Atlas by Kurucz et al. (1984) and the corresponding synthetic solar spectrum, which we computed at similar resolution (i.e.  $R = 522\,000$ ). The input model atmosphere is from the ATLAS 9 and assumes  $T_{\text{eff}} = 5777$  K,  $\log g = 4.4377$ , a microturbulent velocity of 1.0 km/s, and chemical abundance according to Anders & Grevesse (1989).

The figure is made up by a dense sequence of positive and negative spikes, which mainly track the residual flux differences in the absorption line profiles. While positive spikes mainly originate from observed lines that are not present in the synthetic model, the negative peaks come from theoretical absorption lines that are too weak or undetected in the observed spectrum. Note, as a striking feature in the plot, that both positive and negative spikes tend to decrease at longer wavelength, and no systematic drift is present in the data distribution. Fig. 5 gives also a direct measure of the intrinsic uncertainty in the input physics of the models; excluding the telluric bands, clearly affecting the residual distribution about 6300 and 6900 Å, the rms value in the plot is  $\pm 0.086$ .

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